Higher Fidelity Estimating: Program Management, Systems Engineering, & Mission Assurance

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Agenda

- Background/Hypothesis
- Research Methodology
- Statistical Analysis and Findings
- Conclusions and Recommendations for Further Research

Background

- Increasing sponsor scrutiny on critical mission functions of Program Management, Systems Engineering, and Mission Assurance (PMSEMA)
  - Risk-averse environment (technical, schedule & cost)
  - PMSEMA functions bear the burden of ensuring programmatic success
  - Rapidly changing requirements & “requirements creep”
    - More robust/numerous processes, procedures, documentations, and program reviews
  - Shinn et. al. (2011) demonstrated costs are increasing over time
  - PMSEMA functions are explicitly targeted as potentially high cost-risk in draft Discovery AO—programs need to adequately fund these critical mission costs and address cost risk appropriately
- Given changing environment, are we as cost analysts accurately quantifying cost and cost risk of PMSEMA?
  - Traditionally modeled as a factor of mission hardware costs. May be problematic:
    - Assumes a linear and perfectly correlated relationship between hardware and PMSEMA costs
    - Based on data that may no longer reflects industry requirements
    - Applied uniformly to all missions without regard for mission class or requirements
      - Underestimates for lower cost missions (which are still subject to stringent requirements, thus requiring significant oversight)
      - Overestimates for higher cost missions (where treating high hardware costs as a direct predictor of PMSEMA costs results in cost-prohibitive estimates)

Background/Hypothesis

- We hypothesize that PMSEMA costs are influenced (and therefore predicted) by more critical factors than just mission hardware costs
  - Programmatic variables, e.g.: Schedule, start year, PI-led (competed/non-competed), etc.
  - Technical variables, e.g.: dry-mass, total power, risk-classification
- Evaluating programmatic and technical variables allows us to quantitatively analyze the impact of mission complexity on PMSEMA costs
- Including additional relevant mission variables will increase the robustness and credibility of PMSEMA costs, while reducing some of the current cost-uncertainty associated with a rapidly changing mission cost element

Methodology: Key Variables

- First we identified the following variables that may impact PMSEMA costs to collect for analysis (and are objective and quantifiable in available datasets):

Potential Predictor Variables		Dependent Variables
Programmatic	**Technical**	Total PM
Total Mission Cost	Total Dry Mass (kg)	Total SE
Total Cost Less Launch Vehicle	Total Power (W, as reported)	Total MA
Total Hardware Cost	Destination	Total PMSEMA
Phase A-D Months	Risk Classification (A-D)	
Mission Start Year	No. of Instruments	
Mission Launch Year		
Competed/PI-Led?		
Discovery, etc.)		
Requirements Document		
Lead Organization		
Contracted Spacecraft?		
No. of Critical Organizations		
Foreign Involvement?		

Methodology: Data Collection & Normalization

- CADRe as primary data source, with some internal APL data
  - Resulted in data set of 31 missions where data was available for (almost) all of the identified variables
  - CADRe Parts A and B for technical and programmatic data; Part C for cost data
  - All costs inflated to $FY15 using NASA New Start Inflation Index
    - Particularly important for apples-to-apples comparison since we are not analyzing cost-to-cost factors; rather statistical analysis of actual costs as a function of specific variables
  - PMSEMA costs defined as ***mission level*** PMSEMA. Excludes any PMSEMA costs associated with the payload and/or spacecraft
  - Hardware costs defined as total WBS 05 and 06 (payload and spacecraft)
  - Final analyses conducted with total mission PMSEMA costs, and not individual WBS 01,02,03 costs
    - Historical data not consistently mapped between the three elements
    - Analysis shows better predictive equations with total mission wrap elements
    - Total costs can be mapped back to WBS 01,02,03 based on an organization's historical allocations

Methodology: Final Data Set

- Final analyses completed with 12 variables (reduced from 18):

Predictor Variables	Quantification/Definition
Total Hardware Cost	Total A-D Spacecraft and Payload costs
Phase A-D Months	Number of Months
Mission Start Year	ATP date in CADRe
Launch Year	Launch Year
Total Dry Mass (kg)	Dry spacecraft mass (kg), including payload
Total Power (W, as reported)	Power as reported in CADRe (inconsistent metric; BOL, Avg, Peak, etc.)
Competed/PI-Led	No/Yes (0/1)
Risk Classification	A-D (1-4 ranking with D being 1 and A being 4)
Contracted SC?	No/Yes (0/1)
No. of Critical Organizations	Managing instituion, Spacecraft contractor, PI institution, and major payload contributors
# of Instruments	No. of instrument suites
Foreign Involvement	No/Yes (0/1)

- Removed variables that were difficult to quantify, not uniformly available, or clearly redundant/dependent:

Variables Removed from Dataset	Reason
Total Mission Cost	Too much dependence on other programmatic variables
Total Mission Cost less LV	Too much dependence on other programmatic variables
Mission Classification	Multiple missions in dataset without classification; some of potential impact captured with PI-led variable
Requirements Document	Inconsistent data; using mission start year as measure of requirements increase
Lead Organization	Difficult to objectively quantify
Destination	Difficult to objectively quantify

Methodology: Final Dataset

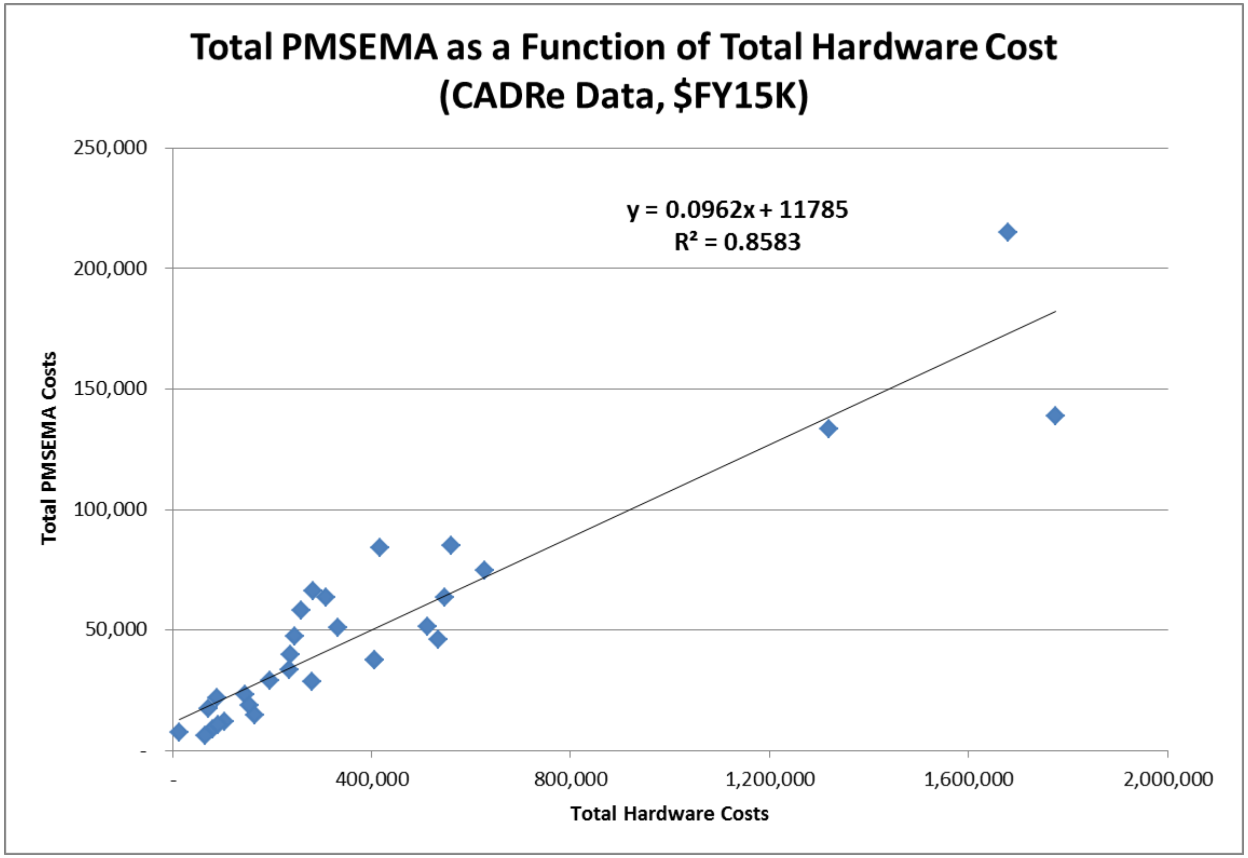
- n=31 in final analysis; fairly robust sample size increases validity of statistical findings
- No missions included with launch prior to 1999
  - Largely a function of available data, but somewhat increases relevancy of any statistical findings to future mission cost estimates

Missions Included in Dataset (with Launch Years)			
AIM	2005	LRO	2009
Aqua	2002	MAP	2001
ChipSat	2002	Mars Odyssey	2001
CloudSat	2006	MER	2003
CONTOUR	2002	MRO	2005
DAWN	2007	MSL	2011
GALEX	2003	New Horizons	2006
Genesis	2001	Phoenix	2007
GLORY	2011	RBSP	2012
GRAIL	2011	SDO	2010
IBEX	2008	Spitzer	2003
JUNO	2011	Stardust	2003
Kepler	2009	Themis	2007
LADEE	2013	STEREO	2006
Landsat-7	1999	TIMED	2001
LCROSS	2009		

Methodology: Statistical Analysis

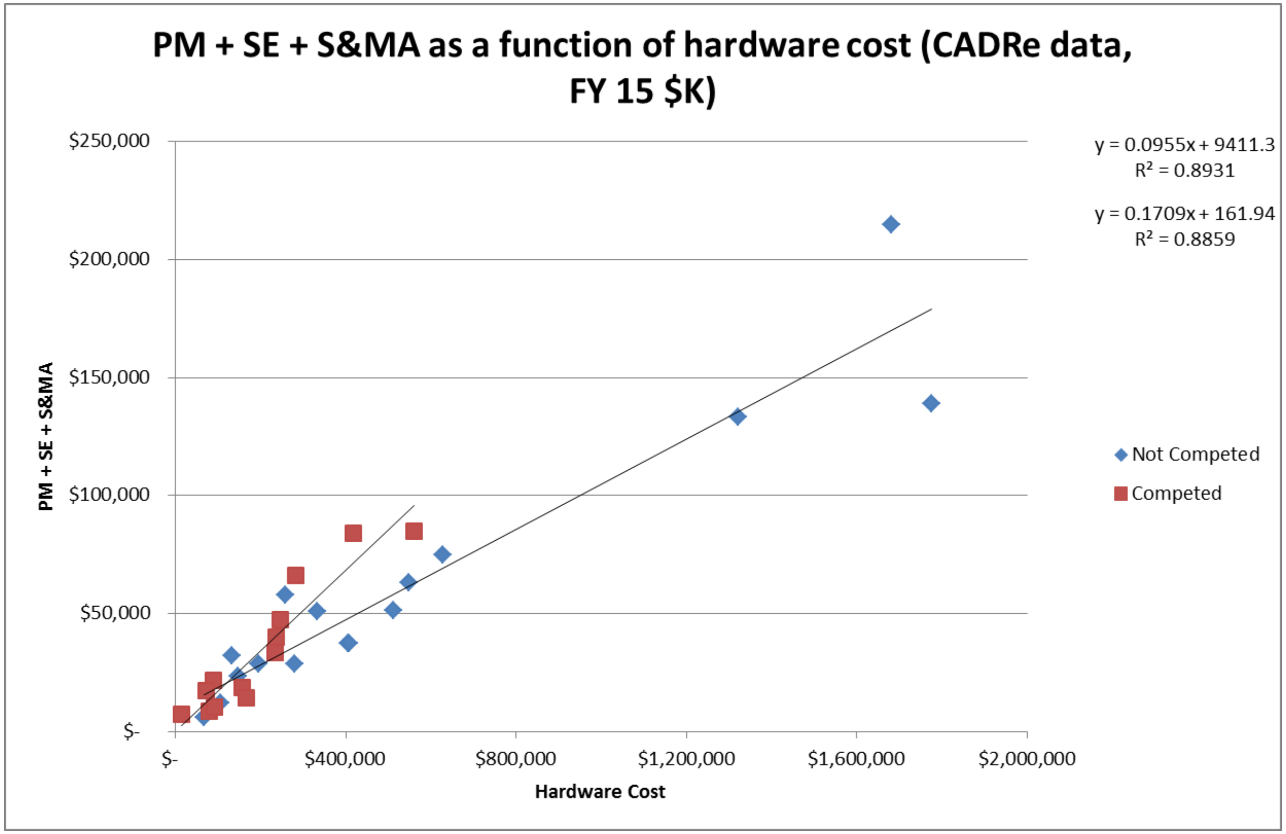
- "Diagnostic" simple single-variable regressions as preliminary means to identify potential cost-drivers and relationships
  - Useful indicators of cost trends (scatterplot analysis)
  - However, correlation is not causation so it is important to conduct multivariate regression to identify all critical cost drivers
- Multivariate regressions & analysis
  - Identify statistically significant cost drivers of PMSEMA
  - Reduce number of input variables based on multicollinearity analysis

Key Single-Variable Regressions: Hardware Costs



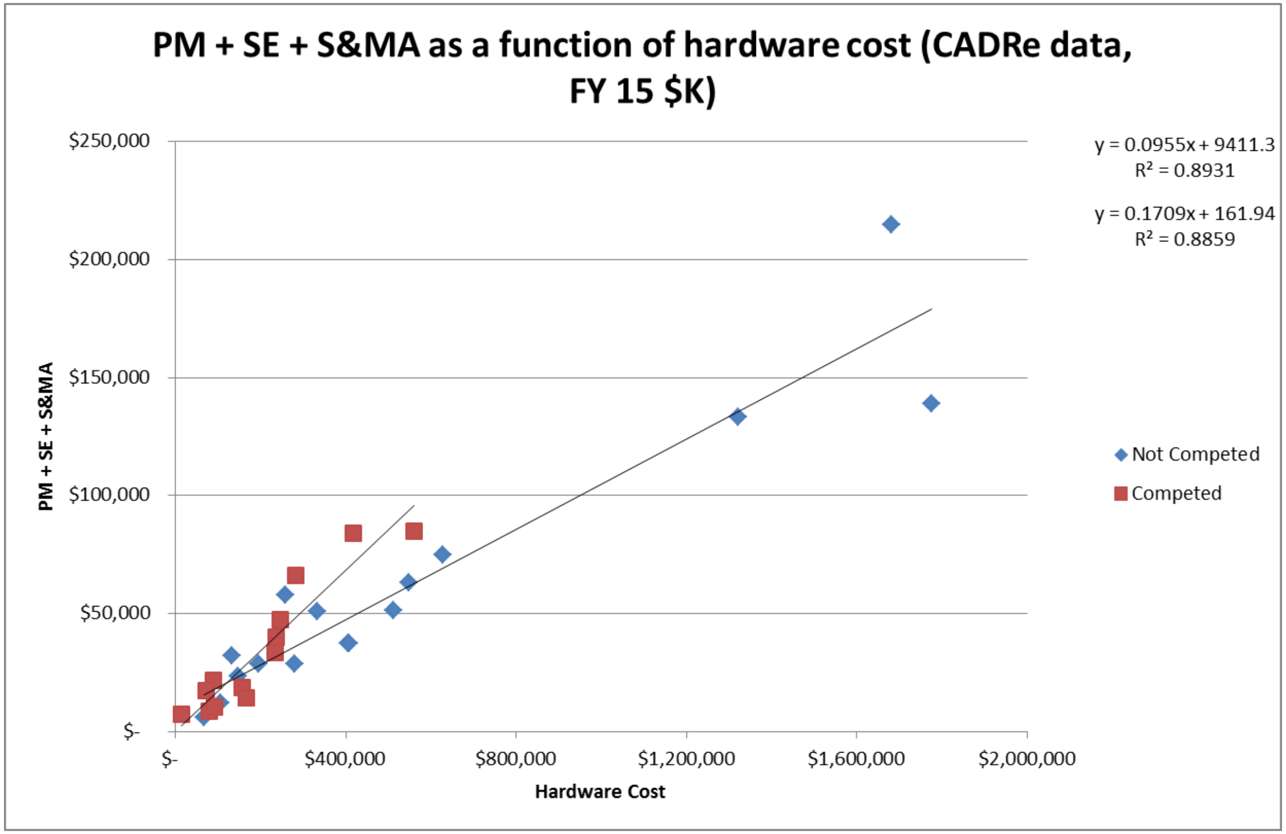
- In aggregate, Total Hardware Cost strongly correlated with total PMSEMA Costs.
- Strong linear relationship (R-squared of 85%)
- Visually can identify two clusters: three in outer cluster are non-competed Flagship missions

Key Single-Variable Regressions: Hardware Costs: Competed vs. Non-competed



- Higher R-squared when normalizing for competed vs. non-competed missions. competed missions.
- Competed missions have higher PMSEMA costs as a function of hardware costs, which makes intuitive sense—they spend more resources to manage total mission cost

Key Single-Variable Regressions: Discovery Missions



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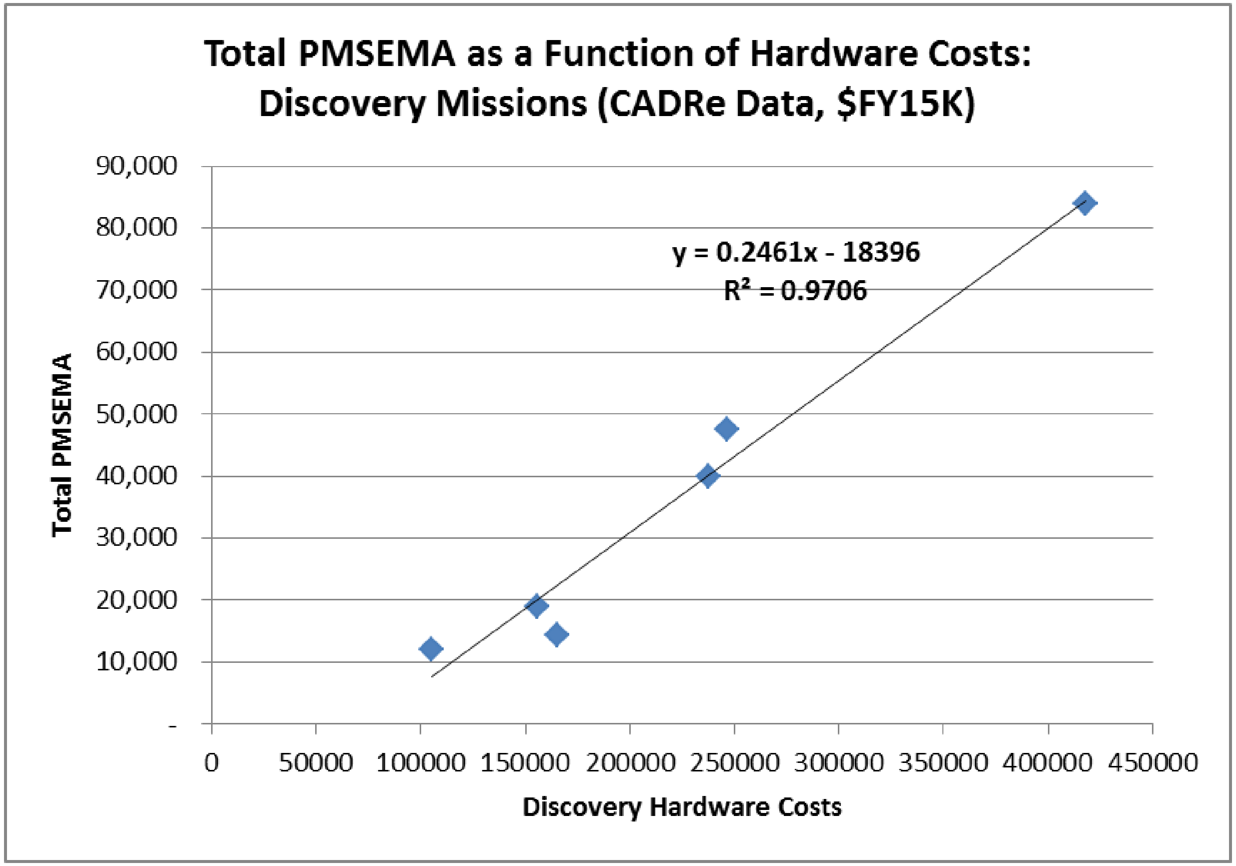
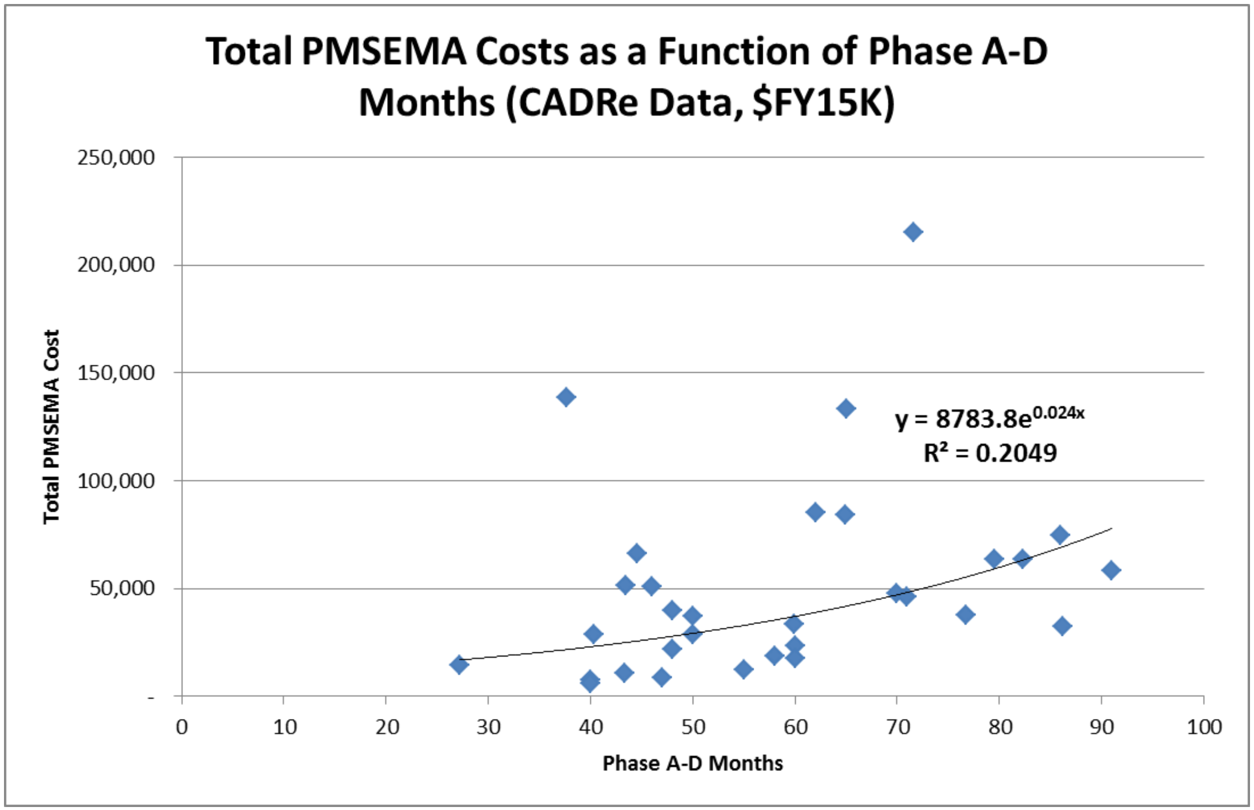
Key Single-Variable Regressions: Discovery Missions



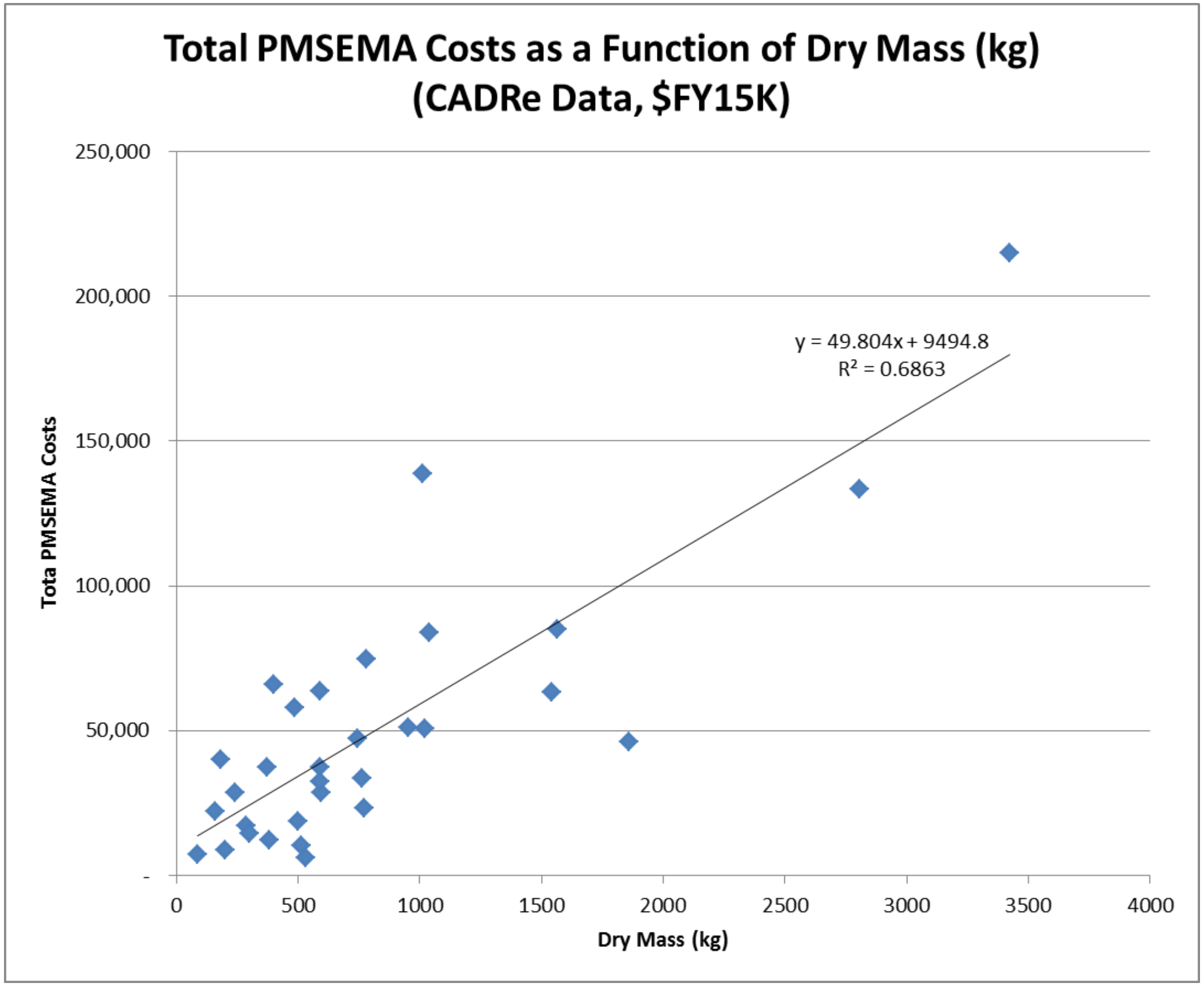
- Extremely linear relationship between total hardware costs and total PMSEMA for Discovery-class missions
- Very high R-squared of 97%; predicts roughly 16-18% of total hardware costs for PMSEMA

Key Single-Variable Regressions: Phase A-D Schedule Duration (Months)



- Surprisingly weak relationship between PMSEMA costs and A-D schedule duration
- R-squared of only 20% using exponential fit

Key Single-Variable Regressions: Dry Mass (kg)



- Dry-mass indicates stronger relationship to total PMSEMA costs than Phase A-D schedule duration; counter-intuitive when estimating essentially LOE-activities
- R-squared of 69%; fairly robust

Multivariate Regression Analysis

- Ordinary Least Squares (OLS) Regression Analysis
- P-value < 0.10 to reject the null hypothesis
- Analysis of Multicollinearity and Heteroscedasticity to ensure:
  - Proper identification of statistically significant variables
  - Verify that OLS linear regression is an appropriate analysis tool
  - Reduce number of overly correlated predictor variables
- Begin with OLS regression of 12 variables presented on slide 7 on total mission PMSEMA costs
  - Variables are not weighted
  - "Dummy" Bernoulli variables for yes/no inputs, e.g. Competed/PI-Led

Independent Variables		**Dependent Variable**
Programmatic	**Technical**	Total PMSEMA
Total Hardware Cost	Total Dry Mass (kg)	
Phase A-D Months	Total Power (W, as reported)	
Mission Start Year	Risk Classification (A-D)	
Competed/PI-Led?	No. of Instruments	
Contracted Spacecraft?	No. of Instruments	
No. of Critical Organizations		
Foreign Involvement?		

Initial 12-Variable Regression Results

Regression Statistics	
Multiple R	0.97873
R Square	0.95790
Adjusted R Square	0.92984
Standard Error	11927.80948
Observations	31

Great! High R-squared and extremely significant F-value for the regression as a whole!

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	58273333507	4.86E+09	34.13	6.85292E-10
Residual	18	2560907500	1.42E+08		
Total	30	60834241007			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-3975970.77	1325532.69	-3.00	0.01	-6760811.61
Total Hardware Cost	0.07	0.01	5.78	0.00	0.05
Phase A-D Months	427.41	204.99	2.09	0.05	-3.26
Mission Start Year	1895.81	2529.72	0.75	0.46	-3418.95
Launch Year	75.32	2737.75	0.03	0.98	-5676.47
Total Dry Mass (kg)	9.91	7.72	1.28	0.22	-6.30
Total Power (W)	-1.28	1.89	-0.68	0.51	-5.26
Competed?	11079.61	6741.52	1.64	0.12	-3083.80
Risk Classification	5293.87	4828.98	1.10	0.29	-4851.44
Contracted SC?	-6470.41	5990.45	-1.08	0.29	-19055.89
No. of Critical Organizations	1256.16	1702.71	0.74	0.47	-2321.11
No. of Instruments	203.92	1562.72	0.13	0.90	-3079.22
Foreign Involvement	-4510.80	5805.19	-0.78	0.45	-16707.05

However…only two variables are statistically significant out of 12. This given the extremely significant F-value for the regression points to some degree of multicollinearity…

Correlation Analysis: Summary

	Total Hardware Cost	Phase A-D Months	Mission Start Year	Launch Year	Total Dry Mass (kg)	Total Power (W)	Compet-ed?	Risk Classific-ation	Contract-ed SC?	No. of Critical Organiza-tions	No. of Instrum-ents	Foreign Involvem-ent
Total Hardware Cost	1											
Phase A-D Months	0.136	1										
Mission Start Year	-0.035	-0.054	1									
Launch Year	0.009	0.106	0.956	1								
Total Dry Mass (kg)	0.779	0.335	-0.024	0.064	1							
Total Power (W)	0.253	0.171	0.112	0.120	0.435	1						
Competed?	-0.402	-0.356	0.038	-0.036	-0.377	0.098	1					
Risk Classification	0.540	0.096	-0.185	-0.149	0.443	0.228	-0.074	1				
Contracted SC?	-0.333	-0.152	0.089	-0.014	-0.252	0.084	0.325	0.023	1			
No. of Critical Organizations	0.805	0.286	0.067	0.160	0.823	0.126	-0.265	0.411	-0.24	1		
No. of Instruments	0.611	-0.188	0.224	0.238	0.470	0.203	-0.197	0.419	-0.34	0.536	1	
Foreign Involvement	0.302	-0.040	-0.038	-0.099	0.182	-0.079	-0.256	0.233	-0.18	0.271	0.275	1

- Dry Mass very highly correlated with total hardware cost (.78…thankfully); which is the better predictor of mission PMSEMA?
  - Run separate regressions—see following slides
- Number of instruments highly correlated with number of critical organizations—remove critical organizations:
  - Data is suspect & redundant with number of instruments
  - No. of critical organizations also very highly correlated with total hardware cost and dry mass
- Mission Start Year highly correlated with Launch Year: remove launch year since start year reflects requirements definitions

Adjusted 8-Variable Regression with Dry Mass (excluding hardware costs)

Regression Statistics	
Multiple R	0.8943
R Square	0.7998
Adjusted R Square	0.7270
Standard Error	23526
Observations	31

Moderately robust R-squared and extremely significant F-value for the regression as a whole

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	48657378135	6082172267	10.98869	4.0994E-06
Residual	22	12176862872	553493766.9		
Total	30	60834241007			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-5065174	2125741	-2.383	0.026	-9473691
Phase A-D Months	137.072	291.985	0.469	0.643	-468.467
Mission Start Year	2513.734	1059.838	2.372	0.027	315.764
Total Dry Mass (kg)	42.760	8.169	5.234	0.000	25.819
Total Power (W)	-2.675	2.792	-0.958	0.348	-8.466
Competed?	4153.964	10585.938	0.392	0.699	-17799.927
Risk Classification	19244.461	7787.366	2.471	0.022	3094.452
Contracted SC?	-16532.570	9444.673	-1.750	0.094	-36119.623
Foreign Involvement?	388.098	10143.188	0.038	0.970	-20647.588

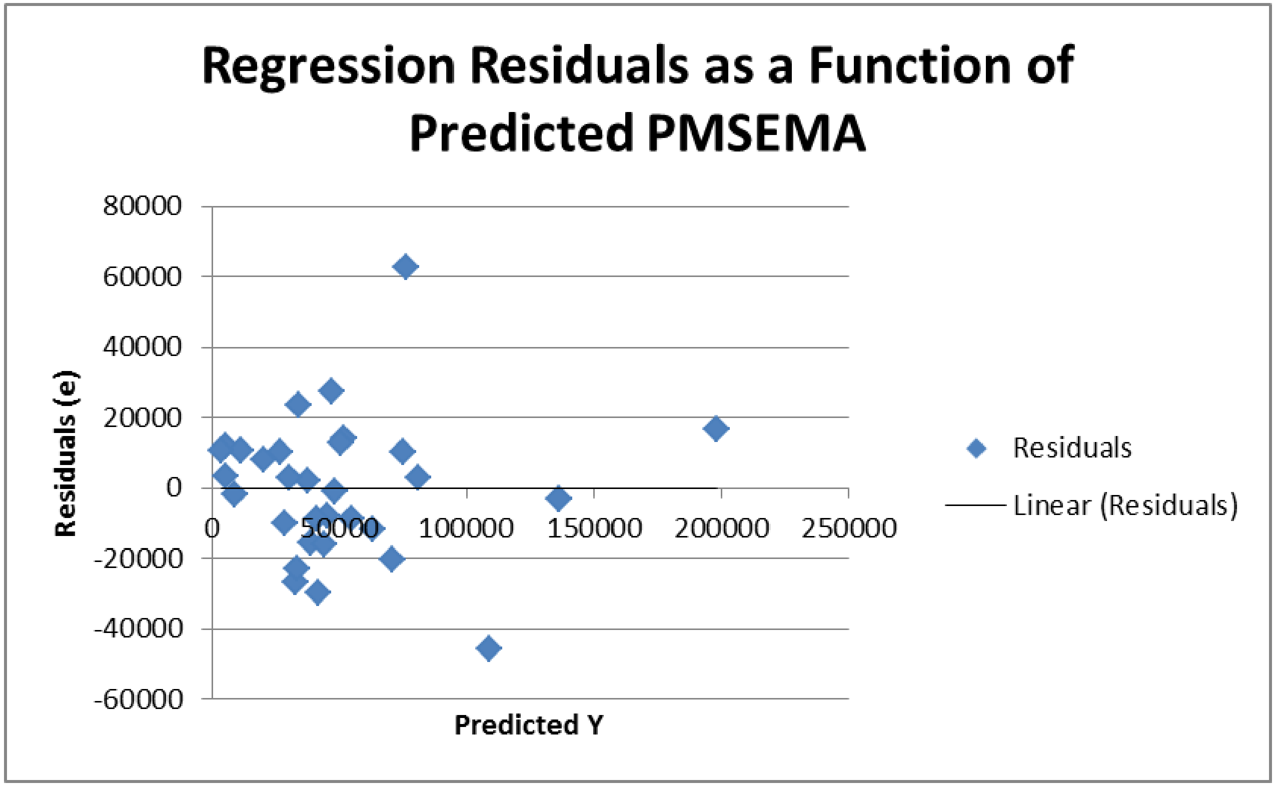
Now we've increased from two statistically significant variables to 4, and Dry Mass is clearly a significant driver. Coefficients are of the expected signs. Is Multicollinearity still a concern?

Correlation Analysis: Dry-Mass Regression

	Phase A-D Months	*Mission Start Year*	*Total Dry Mass (kg)*	*Total Power (W)*	*Competed?*	*Risk Classificati-on*	*Contracted SC?*	*Foreign Involvement ?*
Phase A-D Months	1							
Mission Start Year	-0.054	1						
Total Dry Mass (kg)	0.335	-0.024	1					
Total Power (W)	0.171	0.112	0.435	1				
Competed?	-0.356	0.038	-0.377	0.098	1			
Risk Classification	0.096	-0.185	0.443	0.228	-0.074	1		
Contracted SC?	-0.152	0.089	-0.252	0.084	0.325	0.023	1	
Foreign Involvement?	-0.040	-0.038	0.182	-0.079	-0.256	0.233	-0.177	1

- Predictor variable correlation improved significantly; all $\rho < 45\%$
  - Marginally high correlation between dry mass and power, risk classification

Dry-Mass Regression: Visual Test for Heteroscedasticity



- No quantitative pattern to regression residuals (linear trendline lies on the x-axis)
- Errors are uncorrelated and distributed normally (constant variance)
- OLS valid regression model and we can assume resulting coefficients are unbiased

Adjusted 8-Variable Regression with Hardware Cost (excluding Dry Mass)

Regression Statistics	
Multiple R	0.9692
R Square	0.9394
Adjusted R Square	0.9174
Standard Error	12943.45
Observations	31

Again, high R-squared and extremely significant F-value for the regression as a whole

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	5.715E+10	7.144E+09	42.639775	1.23825E-11
Residual	22	3.686E+09	167532891		
Total	30	6.083E+10			

	Coefficients	*tandard Errc*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-4250657	1173295.3	-3.623	0.00151	-6683922.4
Total HW Cost	0.095	0.008	11.883	0.000	0.078
Phase A-D Months	587.12	160.20	3.665	0.001	254.879
Mission Start Year	2106.40	584.96	3.601	0.002	893.266
Total Power (W)	-0.78	1.43	-0.546	0.591	-3.735
Competed	12147.46	5926.35	2.050	0.052	-143.045
Risk Classification	5133.01	4683.64	1.096	0.285	-4580.266
Contracted SC?	-6173.35	5377.49	-1.148	0.263	-17325.593
Foreign Involvement	-3948.03	5604.62	-0.704	0.489	-15571.301

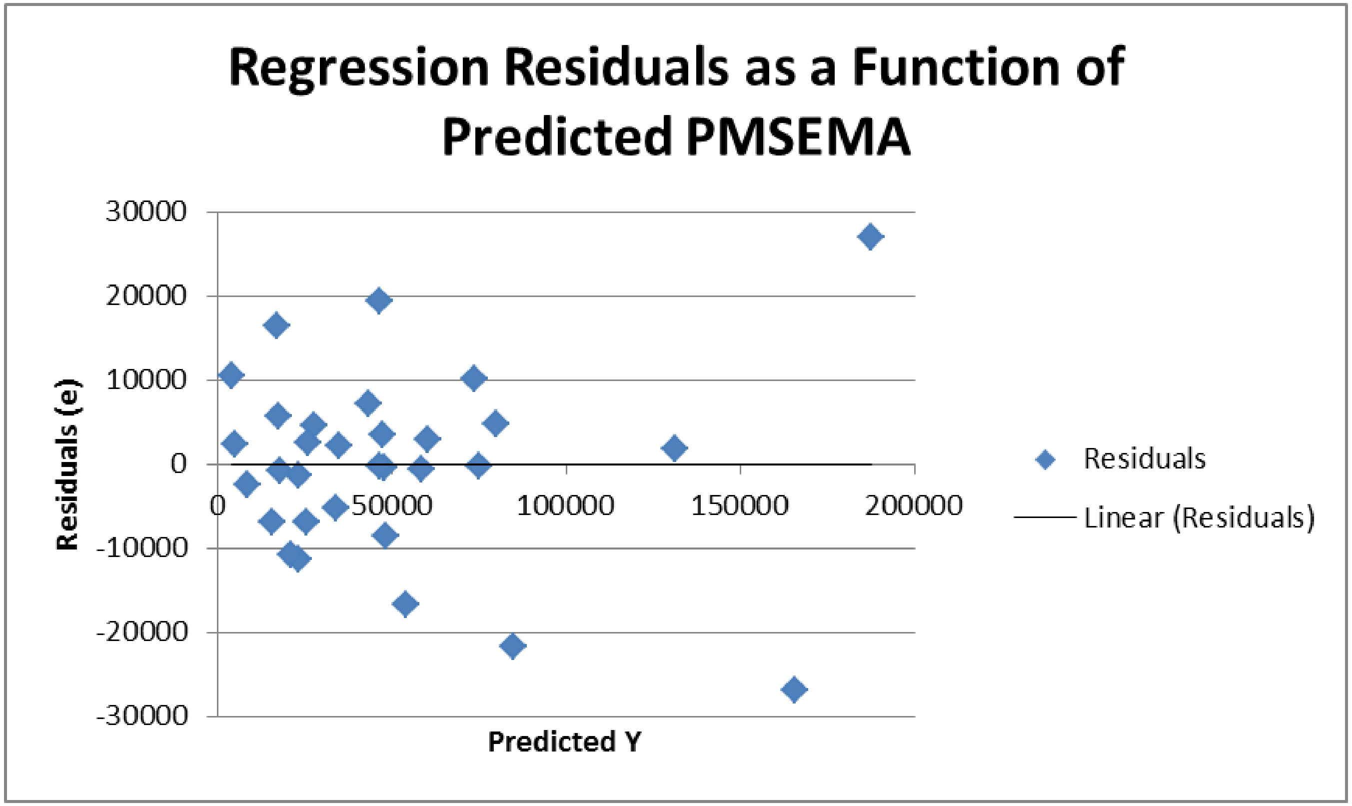
As seen with Dry Mass as one of the predictor variables, we've increased to 4 significant variables (though different variables; again of the expected signs). Is Multicollinearity a concern here?

Correlation Analysis: Hardware Cost Regression

	Total HW Cost	Phase A-D Months	Mission Start Year	Total Power (W, as reported)	Competed	Risk Classificat-ion	Contracted SC?	Foreign Involveme-nt
Total HW Cost	1							
Phase A-D Months	0.1357	1						
Mission Start Year	-0.0350	-0.0544	1					
Total Power (W)	0.2531	0.1714	0.1125	1				
Competed?	-0.4023	-0.3562	0.0377	0.0981	1			
Risk Classification	0.5399	0.0962	-0.1850	0.2279	-0.0736	1		
Contracted SC?	-0.3333	-0.1516	0.0886	0.0843	0.3248	0.0229	1	
Foreign Involvement?	0.3022	-0.0402	-0.0377	-0.0793	-0.2555	0.2329	-0.1765	1

- Predictor variable correlation improved significantly; *almost all* $\rho <$ 50%
  - Total hardware costs strongly correlated with mission risk classification
  - Total hardware costs also correlated with competed/non-competed

Hardware Cost Regression: Visual Test for Heteroscedasticity



- No quantitative pattern to regression residuals (linear trendline lies on the x-axis)
- Errors are uncorrelated and distributed normally (constant variance)
- OLS valid regression model and we can assume resulting coefficients are unbiased

What Happens if we include both Dry Mass and Total Hardware Costs…?

Regression Statistics	
Multiple R	0.978
R Square	0.956
Adjusted R Square	0.935
Standard Error	11509
Observations	31

Highest R-squared of three regressions and extremely significant F-value for the regression as a whole

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	58185035829	5818503583	43.92641	2.08917E-11
Residual	20	2649205178	132460259		
Total	30	60834241007			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-4121139	1138624	-3.6194025	0.0017095	-6496267
Total Hardware Cost	0.0774	0.0095	8.1677	0.0000	0.0576
Phase A-D Months	505.30	164.70	3.0680	0.0061	161.7419
Mission Start Year	2041.65	569.03	3.5879	0.0018	854.6624
Total Dry Mass (kg)	14.15	5.24	2.6983	0.0138	3.2114
Total Power (W)	-2.25	1.37	-1.6387	0.1169	[illegible]
Competed?	13912.75	5317.32	2.6165	0.0165	2821.0042
Risk Classification	4354.25	4403.32	0.9889	0.3345	-4830.9262
Contracted SC?	-5275.23	5133.71	-1.0276	0.3164	-15983.9561
# of Instruments	626.33	1416.14	0.4423	0.6630	-2327.6951
Foreign Involvement?	-3777.19	4994.35	-0.7563	0.4583	-14195.2244

We've also increased to 5 (very) statistically significant variables; however, this data should be treated with care due to the known high correlation between Hardware Cost and Dry Mass.

Correlation Analysis: Including Hardware Cost and Dry Mass

	Total Hardware Cost	*Phase A-D Months*	*Mission Start Year*	*Total Dry Mass (kg)*	*Total Power (W)*	*Competed?*	*Risk Classificati-on*	*Contracted SC?*	*# of Instruments*	*Foreign Involvement*
Total Hardware Cost	1									
Phase A-D Months	0.136	1								
Mission Start Year	-0.035	-0.054	1							
Total Dry Mass (kg)	0.779	0.335	-0.024	1						
Total Power (W)	0.253	0.171	0.112	0.435	1					
Competed?	-0.402	-0.356	0.038	-0.377	0.098	1				
Risk Classification	0.540	0.096	-0.185	0.443	0.228	-0.074	1			
Contracted SC?	-0.333	-0.152	0.089	-0.252	0.084	0.325	0.023	1		
# of Instruments	0.611	-0.188	0.224	0.470	0.203	-0.197	0.419	-0.337	1	
Foreign Involvement?	0.302	-0.040	-0.038	0.182	-0.079	-0.256	0.233	-0.177	0.275	1

- Re-introducing both Total Hardware Cost and Dry Mass to the analysis increases multicollinearity
  - Doesn’t negate the statistical significance of the overall regression, but it does introduce error in the predictor variables

Regression Statistics Summary

Using Dry Mass		Using Hardware Cost		Using Hardware Cost and Mass	
Adjusted R-Squared	**0.727**	**Adjusted R-Squared**	**0.917**	**Adjusted R-Squared**	**0.935**
F-Statistic	**4.0994E-06**	**F-Statistic**	**1.23825E-11**	**F-Statistic**	**2.08917E-11**
Signficant Variables	**P-value**	**Signficant Variables**	**P-value**	**Signficant Variables**	**P-value**
Mission Start Year	0.027	Total HW Cost	0.000	Total Hardware Cost	0.000
Total Dry Mass (kg)	0.000	Phase A-D Months	0.001	Phase A-D Months	0.006
Risk Classification	0.022	Mission Start Year	0.002	Mission Start Year	0.002
Contracted SC?	0.094	Competed	0.052	Total Dry Mass (kg)	0.014
				Competed?	0.017
Apparent Multicollinearity?	**No**		**No/Marginal**		**Marginal/Yes**

- Highest R-squared and most significant P-values using both Hardware Cost and Mass as predictor variables; however, this is clearly problematic given the strong relationship between those two variables.
- Using Dry Mass instead of Hardware Cost has lower R-squared, but less correlation between predictor variables
- Using Hardware Cost instead of Dry Mass results in higher R-squared and more statistically significant variables, with a slight increase in predictor variable correlation values

Given apparent Multicollinearity, the first two regressions appear to be the most valuable for predicting total Mission PMSEMA costs; more research required to determine why statistically significant variables differ between the two regressions

Conclusions

- Total Hardware cost remains a strong indicator of total PMSEMA costs, HOWEVER
- Hardware cost is not the *ONLY* significant variable impacting these elements
- Analysis shows that the following variables should be considered in estimating PMSEMA costs at the mission level:

Mission Start Year	Positive coefficient; costs are increasing over time
Total Dry Mass	Positively correlated with Hardware Costs, which drive PMSEMA
Mission Risk Classification	Positive coefficient; higher risk classifications increase PMSEMA requirements/cost
Contracted Spacecraft?	Negative coefficient; lower mission PMSEMA with contracted spacecraft bus
Phase A-D Months	Postive coefficient; LOE activity increases with schedule
Competed/PI-Led	Competed missions expend more resources to control mission costs

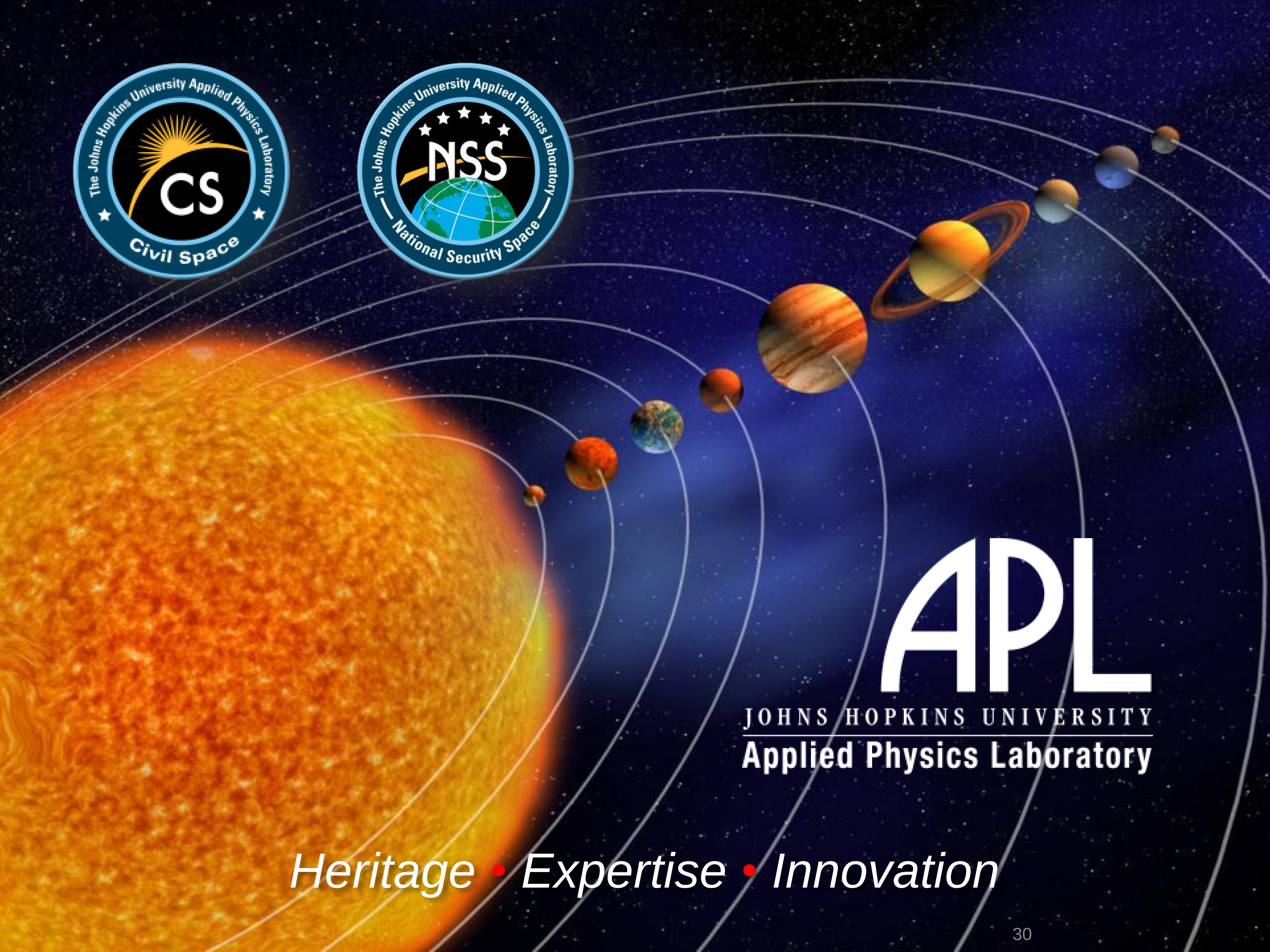
- Recommended equation based on 8-variable regression including Hardware Cost:

Total PMSEMA = -4250657 + .095*HWCost +587*PhaseAD + 2106*MissionStartYear + 12147*PILed + e

- This makes the most intuitive sense since we are already using total Dry Mass as a direct input to Hardware Costs—correlation analysis reveals potential for future analysis on variables that impact Hardware Costs
- Total PMSEMA can be allocated to respective WBS elements based on a given organization's historical trends

Opportunities for Future Research

- Why are the statistically significant variables so different between regressions including Dry Mass and Total Hardware Cost when remaining independent variables are identical?
- More robust quantification of following variables:
  - Mission Classification: not just competed vs. non-competed
  - Mission Destination: quantify environmental impacts on cost, along with impact of fixed launch window for planetary missions
  - Impact of technology development: will require significantly more research into CADRe documentation
- Identification of other quantifiable variables that may impact PMSEMA costs?
- PMSEMA costs are clearly increasing over time: should we expect a rate of change to decrease in future years?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